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THE VISIBLE RADIATION FROM CARBON.

By Edward L. Nichols.

Investigations on Light and Heat, made and published wholly or in part with Appropriations from the Rumford Fund.

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The law of radiation has for a long time been considered by physicists as a subject of high interest, and numerous investigations looking to the establishment of a general relation between radiation and temperature have been made both from the theoretical and the experimental standpoint. The earliest attempts to determine incandescence in its relation to temperature were made with platinum. Draper † in 1847 made observations upon a wire of that metal heated by an electric current. The temperatures were determined from the expansion of the wire. Zöllner ‡ in 1859 compared the light emitted by incandescent platinum with the heat evolved. E. Becquerel,§ who made an extensive study of visible radiation from various solids at high temperatures, used thermo-elements of platinum and palladium, calibrated by reference to melting points with the air thermometer. A partial separation of the rays was effected by means of colored screens.

Becquerel found that opaque bodies, such as lime, magnesia, platinum, and carbon, at the same temperature had very nearly equal emissive powers, a conclusion vigorously contested by his contemporaries, but explained, in the light of later work, by the fact that the glowing bodies were enclosed in a long earthen tube. The conditions for ideal blackness were thus approximately fulfilled. He likewise made photometric observations upon wires electrically heated and found the light to increase much more rapidly than the emitted heat.

Although some of Becquerel's results were at fault, particularly his estimation of temperature above the melting point of gold, his work is especially noteworthy in that he employed many of the methods to which,

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* An investigation carried on in part by means of an appropriation from the Rumford Fund. Read at the meeting of the American Association for the Advancement of Science in New York, June 27, 1900.

† Draper, Philosophical Magazine, XXX. 345 (1847).

‡ Zöllner, Photometrische Untersuchungen (1859).

§ Becquerel, Annales de Chimie et de Physique, (3), LXVIII. 47 (1863).

in the hands of later investigators, our knowledge of the laws of incandescence is due. He established the direct proportionality of the logarithm of the intensity of radiation to the temperature and pointed out the possibility of optical pyrometry.

In 1878 Crova * used the Glan spectrophotometer in the comparison of various sources of light, such as candles, gas flames, the lime light, the arc light, and sunlight, and proposed an optical method for the measurement of temperatures.

In 1879 † I published the results of a series of measurements made in this manner upon the visible radiation from platinum at various temperatures. At that time, the measurement of high temperatures by means of thermo-elements, of platinum and platinum-rhodium, or platinum-iridium, had not been developed, and the determination of the temperature from the change of resistance of the metal was, as has been previously pointed out by Siemens, a matter of great uncertainty on account of the varying performance of different samples of platinum. This difficulty, which was due to the impurities contained in the metal, has since been largely overcome, and platinum thermometry has, through the study of Callendar and others, been advanced to the position of an operation of precision, but at that time I was forced to content myself in the investigation just referred to with an expression of temperature of the glowing platinum in terms of its increase of length.

Work upon the incandescence of carbon was first taken up in a serious manner after the development of the incandescent lamp.

Schneebeli,‡ in 1884, made some observations upon the total radiation and candle power of the Swan lamp. He made no estimation of temperatures.

In the same year Schumann § published his very complete spectrophotometric comparison of the various incandescent lamps in use in Germany. Lucas, ‖ in 1885, heated arc-light carbons *in vacuo*, estimated their temperature from the current employed, and measured the light given in carcels. I shall refer to his work in some detail later.

In 1887 H. F. Weber ¶ began his studies of the spectrum of the in-

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* Crova, Comptes Rendus, LVII. 497 (1878).

† Nichols, Ueber das von glühendem Platin ausgestrahlte Licht. Göttingen, 1879; also American Journal of Science, XVIII. 446 (1879).

‡ Schneebeli, Wiedemann's Annalen, XXII. 430 (1884).

§ Schumann, Elektrotechnische Zeitschrift, V. 220 (1884).

‖ Lucas, Comptes Rendus, C. 1454 (1885).

¶ Weber, Wiedemann's Annalen, XXXII. 256 (1887).

candescent lamp. He found that the first light to appear was not that of the region nearest the red end of the spectrum, but corresponded in wave length to the region of maximum luminosity, and that at these low temperatures the spectrum was devoid of color. Stenger * in the same year corroborated Weber's observations and offered what has since been received as the proper explanation of the phenomenon.

In 1889 I published in collaboration with W. S. Franklin † a series of spectrometric comparisons of incandescent lamps maintained at various degrees of brightness. No attempt was made to determine temperatures. In 1891 H. F. Weber ‡ read a paper at the Electrotechnical Congress in Frankfurt on the general theory of the glow-lamp. By means of numerous measurements through a wide range of incandescence made upon lamps with treated and untreated filaments, constants were established for his empirical formula for the relation of radiation and temperature.

The infra-red spectrum of carbon has, since the appearance of the incandescent lamp, likewise been subjected to measurement. Abney and Festing § in 1883 published curves for the distribution of energy in the spectrum of such lamps from measurements made with the thermopile. In 1894 I compared, with the help of the same instrument and a highly sensitive galvanometer, the infra-red spectra of lamps with black and gray filaments. ‖

Of late years attention has been devoted especially to the problem of the law of radiation from an ideal black body, and various formulae have been proposed by means of which the rise of radiation of any single wave length upon the one hand, and of the total radiation on the other, may be expressed as a function of the temperature. Interesting as this phase of the problem is from the point of view of theoretical physics, it is perhaps even more important to know the relation between temperature and radiation for actual surfaces.

Apparatus and Outline of Method.

I propose in the present paper to describe an attempt to measure the temperature of carbon rods rendered incandescent by the passage of an

* Stenger, Wiedemann's Annalen, XXXII. 271 (1887).

† Nichols and Franklin, Am. Jour. of Science, XXXVIII. 100 (1889).

‡ Weber, Bericht des internationalen Elektrotechniker-congresses zu Frankfurt am Main, p. 49 (1891); also Physical Review, II. 112.

§ Abney & Festing, Philosophical Magazine, (5) XVI. 224 (1833); also Proceedings of the Royal Society, XXXVII. 157 (1884).

‖ Nichols, Physical Review, II. 260 (1894).

electric current, and to make spectrophotometric comparisons of the visible radiation from their surfaces with the corresponding wave lengths in the spectrum of an acetylene flame.

The carbons used for this purpose were produced by the well-known process of squirting a semi-fluid carbonaceous paste through a cylindrical opening. They were straight cylindrical rods 10 cm. in length, and 2 mm. in diameter. Still larger rods would have been preferable, but I was unable to obtain any of greater diameter than the above that were capable of withstanding the temperatures to which it was necessary to heat them. The rods were mounted horizontally in a massive metal box 40 cm. in length, 20 cm. wide, and 20 cm. in height. This box, which was made especially for this investigation, had openings at the ends, through which, by means of air-tight plugs, the terminals of the carbon could be introduced. Through one of these plugs, likewise, the platinum and platinum-rhodium wires of the thermo-element, by means of which the temperature measurements were made, entered the box. In one of the vertical sides of the box was a row of five circular plate-glass windows, which could be removed for cleaning, through which the carbon could be seen and the spectrophotometric observations could be made. Other openings in the top of the box and through the opposite sides served to connect it with a mercury air pump of the Geissler type and for the introduction of manometers for the measurement of pressure. A vertical cross-section of this part of the apparatus is shown in Figure 1. Attempts

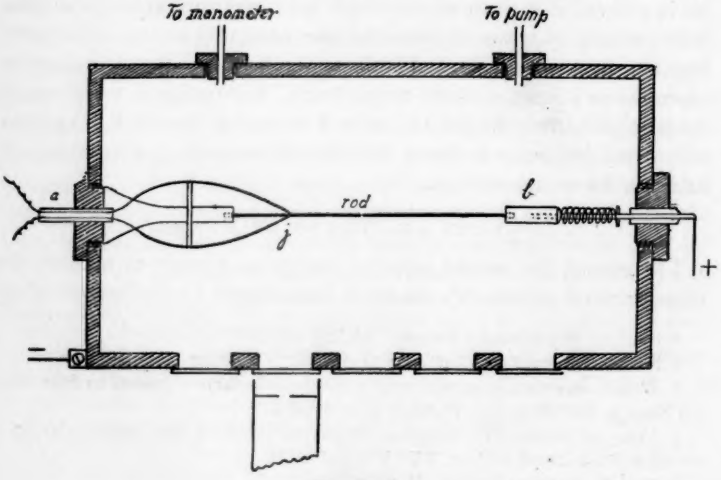

FIGURE 1.

to locate, by a variety of methods, the hot junction of the thermo-element, by means of which the temperature of the surface of the rods was to be measured, in such manner that it would assume the temperature of that surface, made it only too clear that herein lay one of the chief difficulties of the investigation. It was found that such a junction, however small its size, and however carefully it might be brought into contact with the surface of the rod, would not take even approximately the temperature of that surface; and recourse, after the failure of numerous other expedients, was had to the following plan, which although far from being free from objection, was found to be upon the whole the most reliable, and to give, when properly carried out, the most definite and satisfactory result.

By means of a drill made for the purpose from the smallest obtainable size of steel sewing-needle, a minute hole was bored radially at a point upon the surface of the rod lying within the field of view of the spectrophotometer. This hole had an approximate diameter of 0.03 cm. It extended to a depth equal to about one half the radius of the rod and was conical in form. Platinum and platinum-rhodium wires to be used for the thermo-element were drawn to a diameter of 0.016 cm., and their free ends having been laid together side by side, were fused in the flame of the oxyhydrogen blowpipe so as to form a junction. This junction, which after the action of the blowpipe took the shape of a small bead of the combined metals, was trimmed down into conical form, until it would just enter the hole in the side of the rod, care being taken that the entire junction was beneath the surface. The wires leading from this junction were next sealed into a glass tube of about 2 mm. bore, through the interior of which they were carried from end to end, care being taken that they should be nowhere in contact. They were held in place by fusing the glass around them at either end of the tube. This tube was inserted through an opening in the plug *a* (Figure 1) carrying one terminal of the rod, and there made air tight by means of cement. One end of the carbon rod was then inserted in a clamp attached to the inner face of the plug, and the wires at a distance of about 1 cm. from the junction were bent downward at right-angles, so as to bring the junction into position for insertion into the hole in the rod, and to hold it there when inserted by the slight but sufficient spring-action of the wires themselves. This arrangement of the junction and rod is indicated in Figure 2.

FIGURE 2.

The introduction of the thermo-element having been successfully carried out by the method just described, it was possible to insert the plug, carrying the rod and thermo-junction with it, into the end of the box and to secure it in place; after which the free terminal of the rod was introduced between the jaws of a strong clip attached to the opposite plug (*b*, Figure 1). This operation had to be performed through the open windows in the side of the box. These were then screwed rightly into place, and the box was ready for the exhaustion of the air.

This method of measuring the temperature of the surface, to be successful, involved the fulfilling of several rather difficult conditions and the application of an important correction. To bore into the material of a carbon rod carrying a current in the manner described, necessarily disturbs more or less the flow of the current; and the changes of resistance thus introduced are likely to bring about decided changes of temperature in that neighborhood. In some instances this became obvious when the rod was heated, the temperature being higher near the hole than elsewhere. Indeed, it was often possible to note this effect with the eye on account of the increased incandescence of the region in question. In all such cases the mounting was rejected. It was found possible, however, to so nearly compensate for this loss of carbon by the introduction of the platinum junction that no difference in the incandescence of the surface could be detected by the closest observation; and since differences of temperature which cannot be detected by the eye will be negligible in spectrophotometric work, this was taken as the criterion of a satisfactory mounting of the thermo-junction. Measurements were attempted only when this condition was fulfilled. It is likewise obvious that there is danger from the contact of the two wires of the thermo-junction with the sides of the hole in the rod. A branch circuit for the passage of the current is thus formed which includes the galvanometer coils, thus imperilling the integrity of the readings of the electromotive force. This could be obviated only by having the wires touch the rod at points in an equipotential surface, and the fulfilment of this condition was determined by the reversal of the current through the rod and the absence of any effect of such reversal upon the galvanometer.

Another and more serious objection to the method, and one which could only be met by the introduction of a correction, lay in the fact that even with the smallest wires which could be used for a thermo-element a certain amount of heat would be carried away by conduction through the metal; so that the junction would never reach the full temperature of the surfaces with which it was in contact. I was at first inclined to think

that this correction would be a small one, but attempts to measure in a similar manner the temperature of the acetylene flame indicated that the loss of heat from this source was by no means to be neglected. These attempts are described in a subsequent section of this paper.

The numerical value of this correction was accordingly determined by direct experiment in the following manner. Thermo-elements drawn from the same pieces of wire but differing considerably in diameter were prepared. These were inserted two at a time in holes on opposite sides of a carbon rod and the rod was brought to incandescence by means of the current. The temperatures reached by these junctions were compared by means of the potentiometer, and a curve was plotted showing the relation between the cross-section of the wire in the thermo-element and the temperature of the junction. This curve, extended in the direction of decreasing cross-section, served to indicate

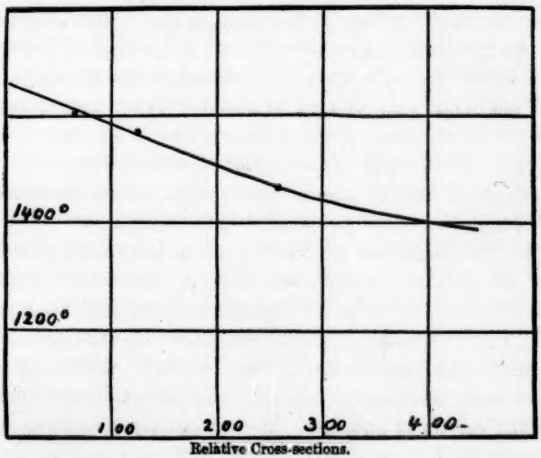

FIGURE 3.

with at least a fair degree of accuracy the temperature which would have been reached by a thermo-element of zero cross-section placed in contact with the surface to be measured. The difference between this temperature and that reached by a junction of any desired size gave the correction which was to be applied. The correction, as will be seen by inspection of the curve, Figure 3, is a very large one, amounting, even in the case of the smallest wires which it was found practicable to use, to

about 85°. The result of the calibration agreed, however, so well with similar experiments made by placing thermo-junctions of various sizes in the non-luminous outer envelopes of the acetylene flame, of the ordinary gas flame, and of the flame of the candle, that I feel warranted in placing much dependence upon them.

The correction is not of the same size in the various cases, but the differences are such as one would expect from the nature of the flames.

This method of correcting for the loss of heat in a thermo-junction was first employed by Waggener * in his investigation of the temperature of the flame of the Bunsen burner. I became acquainted with his research only after the completion of my experiments.

Calibration of the Thermo-Elements.

All our estimates of very high temperatures may be said to rest in one way or another upon extrapolation. The upper limit of usefulness of the air thermometer has been found to lie in the neighborhood of 1500.° At this temperature Erhardt and Schertel, † in their admirable but little known research upon the melting-points of alloys of silver, gold, and platinum, were obliged to abandon direct determination; and, at about the same temperature, Holborn and Wien and Holborn and Day ‡ in their latest studies upon thermo-electric thermometry found that the indications of the air thermometer, even when constructed of the most refractory of modern porcelain, began to be erratic. We have, it is true, the investigations of Violle § upon the melting-points of the metals of the platinum group; but these, it must not be forgotten, are based upon an assumed value for the specific heat, and this assumption is equivalent to the extrapolation of the curve of the variation of the specific heat with temperature. The observed values, by means of which this value was determined, all lie far below those of the melting-points of the metals in question. It is necessary, therefore, in spite of the accumulation of indirect evidence of their approximate accuracy, to hold in reserve the assignment of absolute values of these melting-points until by some means as yet unthought of we shall be able to obtain direct experimental data. In the meantime, they afford us the best present available basis for a temporary scale, our confidence in the

* Waggener, Wiedemann's Annalen, LVIII. 579 (1896).

† Erhardt and Schertel, Jahrbuch für das Hüttenwesen in Sachsen, 1879, p. 154.

‡ Holborn and Day, American Journal of Science, VIII. 165 (1899).

§ Violle, Comptes Rendus, LXXXIX. 702, 1879.

approximate accuracy of which must rest upon the fact that the melting-points for palladium, platinum, etc., as given by Violle are found to lie upon what may reasonably be supposed to be an extension of the curves experimentally determined for lower temperatures by means of the air thermometer. As for the various formulae for the variation of electromotive forces of thermo-elements with the temperature, we must not lose sight of the fact that they are simply analytical expressions for experimentally determined relations, and that the extension of them to temperatures lying far beyond the experimental range is not to be regarded as more trustworthy than the extention of a curve by graphical methods.

Under these circumstances I decided to content myself with the provisional acceptance of the following values for the melting-points of gold, palladium, and platinum, namely: —

Gold,	1075° C
Palladium,	1500° C
Platinum,	1775° C,

and to ascertain as accurately as possible the electromotive force given by the thermo-elements used at these points. It was thought that by drawing a curve through them, and reading intermediate temperatures from this curve, the values obtained would be as close as our present knowledge of the subject will admit. The platinum, platinum-rhodium wire used for my elements was obtained, as has already been stated, from Heraeus in Hanau and was supposed to be of the same stock as that employed by Holborn and Wien. The fact that the electromotive force given by these thermo-elements when exposed to the temperature of melting platinum agreed very closely indeed with that obtained by extrapolation of their data seems to indicate that the metals were identical with those used by them.

Exhaustive studies at the hands of Le Chatelier,* of Barus,† and of Holborn and Wien,‡ and others have led to the conclusion that whenever thermo-elements consisting of platinum on the one hand, and of the alloys of that metal with iridium, rhodium, or any other metals of the platinum group on the other, are to be used in the measurements of

* Le Chatelier, Comptes Rendus, CII. (1866) 819; Journal de Physique (2) VI. 26 (1887); also Mesure des Temperatures Élevées (Paris, 1900), Chapter VI.

† Barus, Bulletin of the U. S. Geological Survey No. 54; also American Journal of Science, XLVIII. 336.

‡ Holborn and Wien, Wiedemann's Annalen, XLVII. 107 (1892); LVI 560 (1895).

high temperatures, it is necessary to make a thorough calibration of the individual thermo-elements involved, or at least of the set of elements manufactured from any given sample of metal. How important it is to perform such a calibration for one's self may be seen from the fact that Holman, Lawrence, and Barr* obtained an electromotive force of .0303 volts from a platinum, platinum-rhodium (10%) element at the temperature of melting platinum, whereas a similar element constructed of wire from Heraeus gave in the hands of the present writer .0182 volts at the same temperature.

Numerous more or less complicated methods of calibration involving the use of various forms of the gas thermometer have been proposed, the carrying out of which involves the use of special apparatus which is difficult of construction and laborious in operation. Fortunately it was possible in the present investigation to substitute for these a new and easy method in which the acetylene flame itself was the source of heat. This method† possesses the advantage of extreme simplicity, and it affords indications the accuracy of which leaves little to be desired.

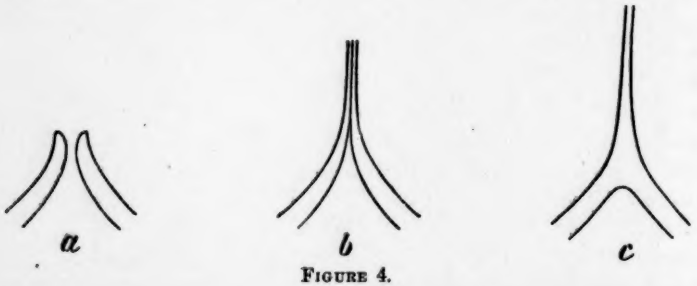

FIGURE 4.

The acetylene flame employed was of the usual flat form produced by the union of two impinging jets. There are three distinct stages observable in the form of such a flame, depending upon the pressure at which the gas is supplied to the burner. In the first, we have two separate cylindrical jets of small size (Figure 4 *a*), which, with increasing gas pressure meet without uniting, each being deflected, by impinging upon the other, into a vertical plane (Figure 4 *b*). At still higher pressures the actual union of the two jets takes place, giving the flame the structure shown in (Fig-

* Holman, Lawrence, and Barr, J. Am. Acad. of Arts and Sciences (1895), p. 218.

† This method of calibration has been separately described in a contribution to the Lorentz Jubilee Volume. The Hague, 1900.

ure 4 *c*), in which the two cylindrical jets of gas in the process of combustion unite to form a single flat vein or envelope which constitutes the luminous portion of the flame. When this third stage is reached, there is great stability of form and position. Such a flame responds with a sharp lateral motion to air waves such as are produced by the slamming of a door, but is comparatively unaffected by slight drafts. Even in a room not essentially free from air currents the lateral motions of the flame, which may be accurately observed by throwing an enlarged image of it, viewed edgewise, upon a screen, rarely amount to more than .1 mm., and in an especially protected place, these lateral movements become entirely imperceptible. The temperature gradient in the layer of air bordering upon the luminous envelope of such a flame is very steep, but it is capable of definite determination by exploration with suitable thermo-elements, and so long as the flame remains undisturbed by lateral drafts its stability is surprising.

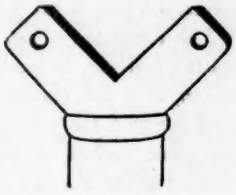

FIGURE 5.

The burner used is of a well-known form (Figure 5), and is made from a single block of steatite. It is mounted upon a horizontal bar of steel (Figure 6), along which it may be moved by means of a micrometer screw. The bar is set up in an inner room without windows, being opposite a circular opening in the wall through which the flame may be observed from without. In this opening is placed the lens of a micro-camera,

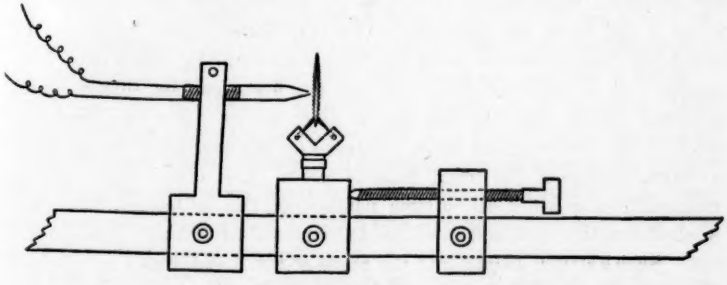

FIGURE 6.

upon the ground-glass screen of which instrument, at a distance of about two meters, an enlarged image of the flame is focussed. The platinum and platinum-rhodium wires to be tested are drawn down to a small

size (diameter about 0.01 cm.), and a thermo-element is formed by cutting pieces of the platinum wire, and of the wire of the alloy to be used, about 70 cm. in length, and binding these to the opposite faces of a rectangular block of wood about 1 cm. in thickness. Beyond this block the wires project about 3 cm. They are bent toward each other until the free ends are in contact, forming a V, and these ends are then fused in the oxyhydrogen flame, forming a junction, which is subsequently trimmed down to the form shown in Figure 7. The apex of the V is cut away until the arch of fused metal joining the two wires is considerably less in thickness than the diameter of the wires themselves, the face of the junction forming a smooth plane surface.

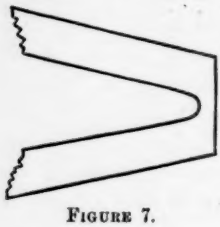

FIGURE 7.

The formation of such a junction becomes, with practice, a simple matter, and can be performed, as it is necessary to do after each observation, in a few moments. The junction is rigidly mounted upon the steel bar with the plane passing through the wires of the V vertical and the plane surface of the metal which forms the face of the junction parallel to the flat face of the acetylene flame. To the free ends of the wires are soldered the copper terminals of the galvanometer circuit, and the junctions are placed in a bath of melting ice. The support carrying the thermo-element is mounted in such a position as to bring the face of the hot junction as nearly as possible into the centre of the field of view of the camera, where it is clearly visible under the illumination of the acetylene flame, which should, at the beginning of the operation, be about 1 cm. from the junction. The micrometer screw, by means of which the flame is moved along the bar, is operated by means of a long handle with a universal joint; so that the flame can be shifted by an observer sitting opposite the ground-glass screen. For the measurement of the electromotive forces produced by the heating of the junction a potentiometer of the usual form is used. The metals the melting temperatures of which are to form points upon the calibration curve, are worked into thin foil, and from this foil strips about .03 cm. in width are cut. Such a strip is looped into the angle of the V and drawn snugly into place, the free ends being cut away until they project only about 1 mm. beyond the face of the junction. To hold this minute loop of metal in its place, it is only necessary to press the foil carefully together around the junction. The thermo-junction carrying the loop having been mounted, in the manner described, in the focus of the camera,

will be clearly seen upon the ground-glass screen, the ends of the loop of metal projecting towards the flame.

The determination of the electromotive force corresponding to the melting-point is made as follows. The observer seats himself in a position where he can watch closely the image of the flame and of the thermo-element and moves the former gradually toward the junction, balancing the potentiometer approximately from time to time as the electromotive force rises with the increasing temperature.

At a definite distance from the luminous envelope of the flame, which distance depends upon the character of the metal under investigation, the projecting ends of the loop will be seen to melt. So quiet is the flame, and so well fixed the temperature gradient from its surface outward when a proper burner is used, and when the flame is placed in a locality reasonably free from air currents, that the fusion of the successive portions of the metal loop may be brought about from the end inward with the greatest nicety; and the electromotive force may be determined at each stage until the fusion has progressed to the plane coinciding with the face of the junction. Even then, in many cases, those portions of the loop of metal which lie within the angle of the junction will remain unfused, although their distance from the melted portion of the loop is only a fraction of a millimeter.

The delicacy of this operation under favorable conditions is very great, and the agreement of the successive readings of the melting-points of a given sample of metal is excellent. It is desirable to make a series of readings, leading up to the true melting-point, for the reason that when the fusion of the metal loop has progressed to that portion which lies in contact with the platinum, an alloy is almost immediately formed between the fused metal and the junction itself, which affects the thermo-electric indications of the couple. For this reason it is not possible to get consistent readings by repeating observations with a given junction. The proper procedure is to cut the wires back 2 or 3 mm. from the apex of the V after each set of readings, and to make a new junction of the proper form from the free ends thus produced. This requires but little time after the operator has gained a reasonable degree of familiarity with the method.

When the metal, the melting-point of which is desired, is platinum itself, the platinum wire of the junction begins to fuse at the same time as the loop, the platinum rhodium or platinum-iridium side remaining unmelted. The precise point at which this fusion of the platinum occurs is, however, quite as definite as in the case of metals of lower melting

temperature. This method has the advantage of avoiding the use of the air thermometer and of furnaces in which fusion of the metals takes place. The amount of metal which it is necessary to melt is almost infinitesimal. The loops used in each observation weigh only a fraction of a milligram, and the operation may be repeated time after time at the will of the observer with the greatest ease. On the other hand it should be noted that the method is applicable only to such metals as will fuse before oxidation in the hot layers of the acetylene flame. It is not practicable with magnesium, aluminium, zinc, or iron, since these oxidize under the conditions of the experiment instead of fusing. For such of the metals of the platinum group as have melting-points below that of the junction itself, and for gold, silver, and copper, the method is a convenient one, and its accuracy is, I believe, fully equal to that of any other method which has thus far been employed. To guard against the deleterious influence upon the thermo-junction of the vapors of the flame, it is important to bring the latter up gradually by the slow action of the micrometer screw in the manner which I have already described. The atmosphere with which the junction is surrounded under these conditions contains an

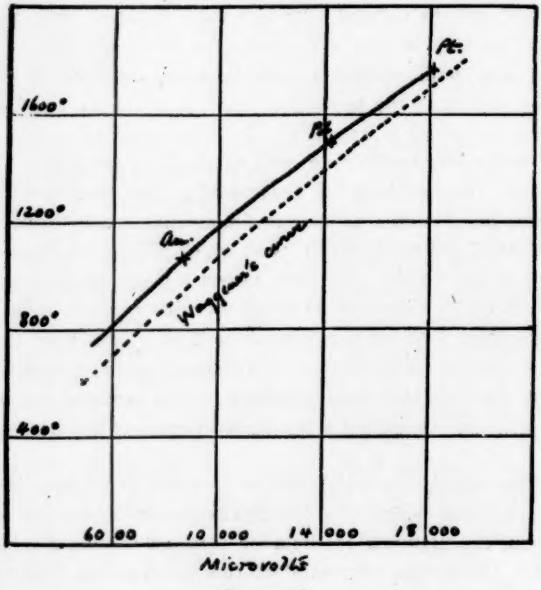

FIGURE 8.

excess of oxygen, and even where the metal to be melted is platinum itself, fusion occurs before the luminous portion of the flame, the action of which upon the thermo-electric properties of the junction is to be feared, has been reached. It is well-known that a junction, the performance of which has been vitiated by exposure to the vapors of a flame or furnace, can be restored to its original condition by immersion in an oxydizing flame. In this method of calibration the junction is continually subject to such oxidation as is necessary to preserve it. Thus one of the sources of error which it has been found most difficult to guard against in the use of the furnace is altogether avoided.

Figure 8 contains the calibration curve of the thermo-elements used in this investigation, and likewise, for purpose of comparison, a curve reproduced from Waggener's paper and extrapolated by him from data given by Holborn and Wien. It will be seen that while the curves are not identical they are of the same character, and that the differences are not greater than experience would lead us to expect in the case of different thermo-elements, even where these are from metals of the same manufacture. It is not a question of absolute electro-motive forces, but of the form of the curves, since what we need is a criterion by means of which to determine whether temperature readings based upon Violle's values for palladium and platinum are in reasonable accord with those obtained by the extension of the curve of Holborn and Wien.

The Spectrophotometer.

The spectrophotometer used was a copy of the instrument designed by Lummer and Brodhun for the Imperial Institute in Charlottenburg. It consists of a one-prism spectroscope with two collimator tubes, placed at right-angles to each other, as shown in Figure 9. Each of these tubes carries a slit the width of which is regulated by means of an accurate micrometer screw with a drum head divided into one hundred parts. By estimating tenths of a scale division, the width of the slits could be estimated to one one-thousandth of a revolution.

The essential feature of this photometer consists in the Lummer-Brodhun prism D, placed between the objective lenses of the two collimators, and the dispersing prism in such a position that the beam of light from one of the tubes is transmitted directly to the latter, while that from the other tube is bent to 90° by total reflection. The instrument was set up with collimator A in such a position that a portion of the surface of the incandescent rod lying nearest to the point at which the thermo-element had been inserted formed a field of illumination for the slit at a distance

of about 25 cm. The region under observation was limited by means of a vertical diaphragm d, 5 mm. in width, which was mounted in a tube in front of a window of the metal vacuum box. The comparison source was the spectrum of the brightest part of an acetylene flame set up in the axis of the other collimator at a corresponding distance, and viewed through a circular aperture c, 5 mm. in diameter, cut in a metal screen interposed between the flame and the slit and as near the former as practicable.

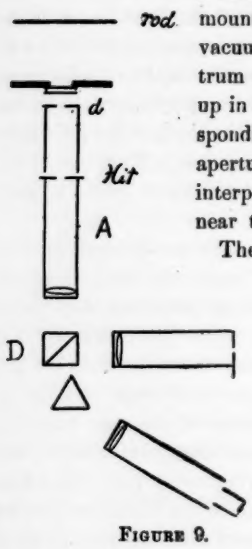

FIGURE 9.

The acetylene flame was adopted as a comparison standard for the following reasons: —

1. It possesses a continuous spectrum, brighter in the less refrangible regions than that of any other controllable source of light.

2. The radiating material is finely divided carbon, presumably of a character not unlike that of the surface of the untreated rod.

3. The acetylene flame is the result of the combustion of a definite fuel (C_2H_2) burning under reasonably constant conditions. It is preferable in this regard to any of the ordinary gas or candle flames in which the fuel is of an undetermined and more or less variable character.

4. When supplied with gas under constant pressure, an acetylene flame of the type used in these experiments, that, namely, obtained by means of a burner composed of a single block of steatite, is more nearly constant in its intensity and color than any other flame with which I am acquainted, with the exception of that of the Hefner lamp. It is indeed questionable whether the latter is superior to acetylene in this respect, and its comparative weakness in the blue and violet renders it very undesirable as a comparison source in spectrophotometry.

*Determination of the Temperature of the Acetylene Flame.**

Concerning the temperature of the acetylene flame, varying and incompatible statements are in existence. The temperature of combustion

* The results of these experiments on the temperature of the comparison flame were separately communicated to the American Physical Society on February 24, 1900, and were published in the Physical Review, X. 234.

of this gas, according to Le Chatelier,* would be, when burned in air, 2100° to 2420°. Measurements with Le Chatelier's pyrometer, on the other hand, made by V. B. Lewes,† gave temperatures lower than those of ordinary gas flames. Lewes found for the obscure zone 459,° for the edge of the luminous zone 1411,° and for the region near the summit of the luminous zone 1517°. Smithells,‡ upon the appearance of the data given by Lewes, described a series of experiments for the purpose of showing that the temperature of the flame reaches, in point of fact, very much higher values than those given by that author, and that in many portions it is higher than the melting point of platinum.

It can be easily shown by inserting wires of platinum into the flat acetylene flame obtained from any one of the forms of burner usually employed, that while the thicker wires remain unmelted, those of very small diameter are readily fused. I found, for example, that a wire having a diameter of 0.0082 cm. became fused at the end with the formation of a distinct globule, before the metal had penetrated the outer luminous layer of the flame, whereas wires of 0.01 cm. or of larger diameter remained unmelted. The experiments of Waggener § show that there are portions of the flame of the Bunsen burner in which it is possible to melt platinum, while MacCrae,‖ working with a platinum-rhodium element, found for the hottest region in the Bunsen flame 1725°. It will be seen from the experiments to be described in this paper, that MacCrae's determination, which was made with wires having a diameter of 0.02 cm., is not incompatible with the observations of Waggener and others. Smithells, in the paper just cited, describes the melting of platinum wires having a diameter of 0.01 cm., in various parts of the outer sheath of a flat flame of illuminating gas. Pellissier,¶ in commenting upon Lewes's measurements, refers to experiments in which minute wires of platinum, made by Wollaston's method of silver plating, drawing, and subsequent dissolving of the silver coating, when thrust into the flame of a candle, melted instantly. I have not been able to find other printed reference to these observations and do not know with whom they originated. An attempt to repeat the experiment with a Wollaston wire having a diameter of 0.0011 cm. resulted in the ready

* Le Chatelier, Comptes Rendus CXXI. 1144 (1895).
† Lewes, Chem. News, LXXI. 181 (1895).
‡ Smithells, Journal of the Chemical Society, LXIX. 1050 (1895).
§ Waggener, l. c.
‖ MacCrae, Wiedemann's Annalen, LV. 97.
¶ Pellissier, L'Éclairage à l'acétylene (Paris, 1897), p. 186.

fusion of the wire by the flame. An examination of the remaining portions under the microscope showed that the metal had been melted down into clean, well-rounded beads, and had not been consumed by oxidation or any other chemical reaction.

Smithells's contention that the temperature of flames cannot be obtained directly from the indications of a thermo-element because of the loss of heat by conduction and by dispersion from the surface of the latter, so that the portions submerged in the flame never arrive at the temperature of the surrounding gases, is well founded. Lewes and likewise Waggener recognized this fact, and in their measurements made use of wires of different sizes.

The apparatus which I employed for the determination of the temperature of the acetylene flame has already been described (see Figure 6). The method was similar to that used in the calibration of the thermo-elements. The electromotive force of the elements, as these were gradually brought into the flame, was measured by means of the potentiometer previously employed in the calibration of the thermo-elements and subsequently in the determination of the temperature of the carbon rods. It consisted of a sensitive galvanometer of the d'Arsonval type and an accurately adjusted resistance box containing coils ranging from 50,000 ohms to 1 ohm. A large Clark cell of the old Feussner type was mounted in series with the resistance box. The thermo-element, the galvanometer, and a subsidiary resistance of 10,000 ohms were looped around a portion of the resistance box, the ratios being varied until complete balance was secured. The electrical connections are shown in Figure 10. The type of standard cell selected for this work is subject to considerable errors from diffusion lag. It has, however, the advantage of being capable of furnishing a much larger amount of current than the small types of cell, in which diffusion lag is avoided, without appreciable loss of electromotive force. Two of these cells were placed side by side in a thick-walled inner room which

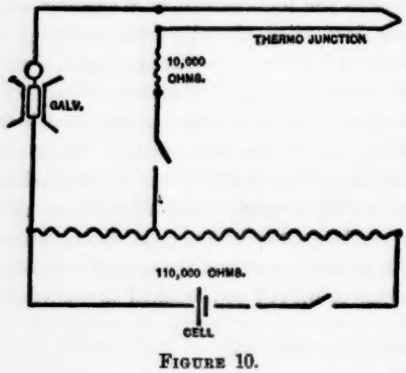

FIGURE 10.

had been constructed for the purpose of securing uniform temperature for the standard clock of the physical laboratory, and other similar apparatus. The range of temperature in this room fluctuated throughout the entire investigation between 18°C. and 19°C. The range was so small and the variations occurred so gradually that no changes of electromotive force of a size which it was necessary to consider in these measurements could have arisen other than those included in the usual correction for temperature.

The two cells were compared with each other from time to time by setting them in opposition to one another in circuit with a sensitive galvanometer and noting the deflection produced. It was found that although one of them was supplying current to the 100,000 ohm circuit of the potentiometer, during the times when it was necessary to close the key of that circuit, the difference of electromotive force between the used and unused cell was always very small, never more than a few hundred thousandths of a volt. At the end of the entire set of measurements, the difference was 0.00006 volts. The absolute electromotive force of these cells was checked by comparison with Clark cells of the H form and of the test-tube form, constructed in this department in 1898. As a result of these comparisons it was found that the electromotive force of the cell used in the potentiometer might be taken at 1.430 volts at 18.°

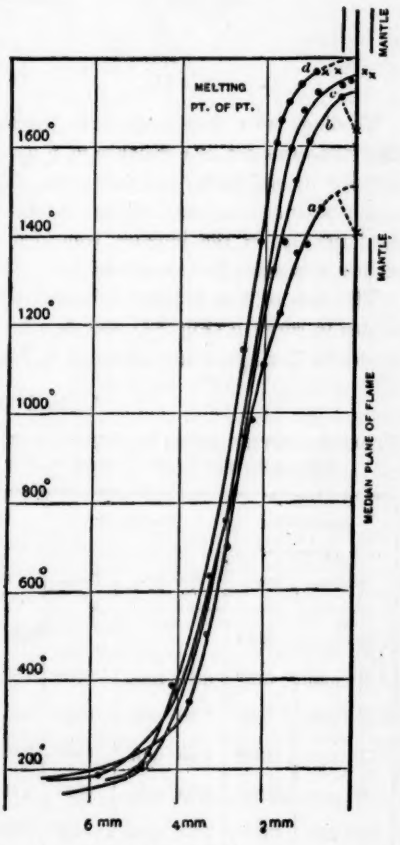

FIGURE 11.

The wires selected for the four junctions to be used in the experiment upon the acetylene flame were measured under a microscope with micrometer stage. Their diameters were as follows: —

Junction I.	Diameter 0.01996 cm.
" II.	" 0.01598 cm.
" III.	" 0.01089 cm.
" IV.	" 0.00821 cm.

Readings were first made with junction I. (diameter 0.01996 cm.). The flame was set at a distance of 6 mm. from the face of the junction, and the potentiometer was balanced. The flame was then moved stepwise nearer and nearer, and the potentiometer rebalanced at each step until the face of the junction coincided with the edge of the luminous mantle at a point just above the apex of the inner non-luminous zone.

The rise of temperature indicated by the potentiometer readings is shown in curve *a* (Fig. 11), the data for which as well as for the other curves in that figure are contained in Table II.

TABLE II.

TEMPERATURES INDICATED BY THERMO-JUNCTIONS I., II., III., AND IV. AT VARIOUS DISTANCES FROM THE MEDIAN PLANE OF THE ACETYLENE FLAME.

Junction I.		Junction II.		Junction III.		Junction IV.	
Distance.	Temp.	Distance.	Temp.	Distance.	Temp.	Distance.	Temp.
5.62 mm.	185°	. . .	. . .	5.42 mm.	165°	4.63 mm.	233°
3.91 mm.	370°	3.65 mm.	353°	4.82 mm.	183°	4.11 mm.	406°
2.85 mm.	760°	3.33 mm.	508°	3.21 mm.	657°	2.55 mm.	1168°
2.09 mm.	1128°	2.90 mm.	595°	2.03 mm.	1278°	2.12 mm.	1411°
1.66 mm.	1229°	2.30 mm.	989°	1.50 mm.	1598°	1.86 mm.	1613°
1.30 mm.	1367°	1.93 mm.	1322°	1.18 mm.	1685°	1.70 mm.	1667°
1.07 mm.	1382°	1.68 mm.	1385°	0.894 mm.	1724°	1.54 mm.	1705°
0.850 mm.	1467°	1.40 mm.	1513°	0.566 mm.	1747°	1.30 mm.	1738°
		1.09 mm.	1617°	0.238 mm.	1759°	1.025 mm.	1771°
		0.320 mm.	1715°	0.00 mm.	1775°	0.780 mm.	Molten.
				−0.29 mm.	Molten.	0.300 mm.	Molten.

The increase of temperature as the flame approaches the junction is gradual at first; but at a distance of about 0.4 cm. from the median plane, the curve suddenly becomes steep. It is probable that this distance measures the thickness of the layer of non-luminous gas which surrounds the visible flame. Outside of this region, the junction is heated almost altogether by radiation. As soon as it penetrates the column of moving gas, however, heat is brought to it principally by convection. Before the surface of the luminous mantle is reached the curve shows indications of approaching a maximum.

Upon pushing the flame still nearer to the junction so that the latter penetrated the luminous region, an accumulation of lampblack began to form upon the wire, with fall of temperature; a process so rapid that at the end of two minutes a button of carbon several millimeters in diameter is formed. This is finally torn loose from the wire by its own weight; whereupon the deposition of a new mass begins. I attempted by watching the breaking away of the carbon from the wire, which occurred at regular intervals, to determine the temperature of the wire before the coating of carbon had begun to show itself again. The highest temperature which it was possible to observe in this way was nearly one hundred degrees below that in the luminous layer, and it was obvious from the movement of the galvanometer needle that the junction was being rapidly cooled by the deposition.

Junction II. (diameter 0.01598 cm.) was now substituted for Junction I., and a similar set of readings were made. This junction, as had been anticipated, showed higher temperatures. It was found possible, owing to the small diameter and consequently high temperature of the wire, to penetrate further into the flame before the deposition of carbon began, so that measurements with the junction actually within the luminous layer could be made. The general form of the curve, as will be seen by inspection of the figure (curve *b*) is the same as that obtained with Junction I. After penetrating the luminous mantle to a small fraction of a millimeter, carbon began to gather upon this junction likewise, with lowering of temperature, as in the case of Junction I. The attempt to read temperatures immediately after the dropping of the accumulated carbon showed that the highest temperature which could thus be observed was again about one hundred degrees below the temperature of the luminous mantle. It was clear in this case, as before, from the rapid fall of temperature already going on, that this reading has no significance.

Similar readings with Junction III. (diameter 0.0108 cm.) gave a third curve of the same type as those plotted from the reading made with I.

and II., but the temperatures were higher throughout. With this junction it was found possible to penetrate to the centre of the flame without the deposition of carbon, the temperature of the wire being apparently too high to permit the formation of soot. Upon pushing through the median plane of the flame to the second luminous mantle, the junction was melted. This result was not unexpected, since the temperature of the junction at the first luminous mantle reached 1750°, so that a rise of twenty-five degrees of temperature would suffice to produce fusion. The wire when pushed through the flame in the manner just described is heated for greater and greater distances back from the junction until the losses of heat at the junction are sufficiently diminished to raise the tips of the wires to the melting-point.

With Junction IV. (diameter 0.0082 cm.), a fourth curve, similar in form to the preceding ones and with still higher temperatures, was obtained. This junction was fused at a distance of 0.075 cm. from the core of the flame, and of 0.037 cm. from the edge of the first luminous mantle. It was easy to observe in the enlarged image upon the plate of the microcamera the melting away of the platinum wire, while the platinum-rhodium alloy was still unaffected, and while contact was still unbroken. A satisfactory observation of the electromotive force of the thermo-element at the melting-point of platinum was thus obtained. This reading (0.018236 volts) differs from the value found in my calibration of the thermo-junctions used in this investigation (0.018262 volts) by a quantity of (0.000026 volts) less than the errors due to changes in the electromotive force of the standard cell. If the latter reading be taken to correspond to 1775°, the former indicates 1773°.

Beyond this point, it was impossible to make direct observations of temperature; but the form of this and the preceding curves were so closely allied that I felt no hesitation in extending the curve *d* to the core of the flame. This has been done by means of dotted lines in the figure. Curves *a* and *b* have been extended in the same manner. In order to form an estimate of the temperature which would have been reached by a thermo-junction of negligible cross-section, provided such a junction could have been obtained which was capable of registering temperatures above that of the melting-point of platinum, the ordinates of the four curves, *a*, *b*, *c*, and *d* were taken for the core of the flame, for the plane of the luminous mantle, for a plane distant 0.07 cm. from the core, and for a plane 0.10 cm. from the core. These readings were plotted and curves were drawn through them as shown in Figure 12; relative cross-sections of the wires being taken as abscissae, the temperatures as

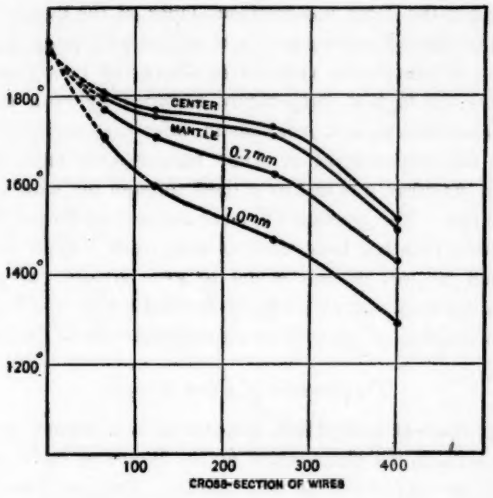

FIGURE 12.

ordinates. If these curves could be extended to the line representing zero cross-section, the temperatures indicated by the points in which each of them cuts that line would give the temperature of the portion of the flame to which the curve corresponds. There is a considerable element of uncertainty in extrapolation even over so short a range as this; but it is obvious from the character of the curves lying within the limits of observation, that each of them trends upward, and it seems highly probable that they all meet the line of zero cross-section at a temperature not far from 1900°. The fact that the curves cut this line at nearly the same temperature would seem to indicate that the distribution of temperatures from the centre of the flame outward for a distance of about 1 mm. is a nearly uniform one.

It would perhaps be unwise to attempt to draw any more definite conclusion from the probable trend of these curves; but I have ventured to extend them in the manner shown in the figure, so that the curve for the region 1 mm. from the centre of the flame reaches the zero of abscissae about twenty degrees above that for the centre of the flame, *i. e.* at 1920°, and the intermediate curves at temperatures lying between them. I regard this as an extreme treatment of the case, and allude to it only to indicate that, in accordance with common belief, the highest temperature

may be found in the outer non-luminous layer of the flame, but that it is unlikely that the difference amounts to more than twenty degrees.

The point of intersection referred to above lies nearly one hundred degrees above the highest temperature recorded by even the smallest of the thermo-elements, and it is safe to infer that nearly all previous attempts at the measurement of flame temperatures must, for lack of correction of the error, due to loss of heat through the wire, be regarded as much too low. The junction IV. is, so far as I am aware, the smallest in cross-section that has been used in such work. With larger wires, the correction for loss of heat would be even greater, except in cases where, as in the observations made by Smithells, and by Waggener, the precaution was taken to immerse an extended portion of the wires within the flame.

Temperature of Other Flames.

For the purpose of comparison, I measured in a manner analogous to that just described, the temperature of the luminous flame of ordinary illuminating gas and the flame of a candle. The gas flame employed for this purpose was obtained from a lava tip rated at one cubic foot and giving a flat flame of the usual form. The image of this flame, when viewed upon the ground-glass screen of my camera, was found to be comparatively ill-defined and unsteady; but although the outlines of the luminous sheath were much less clearly marked than in the case of the acetylene flame, they were discernible. Owing to the continual motion of the flame, due to the small velocity of the gas issuing from the jet, no attempts were made to plot curves of temperatures outside the flame. All readings were made with the junction as nearly as possible in contact with the outer surface of the luminous sheath, at a point in the brightest portion of the flame. This position is approximately indicated by the letter x in Figure 13. The four junctions already described were mounted, one after another, in such a position that the flame could be moved up until they came into contact with the sheath at the point indicated. The temperatures of the junctions when in that position are given in the following table: —

FIGURE 13.

TABLE III.

Junction I.	1385°	Junction III.	1609°
" II.	1484°	" IV.	1676°

These values having been plotted with relative cross-sections of the ires as abscissae, and temperatures as ordinates, were found to lie

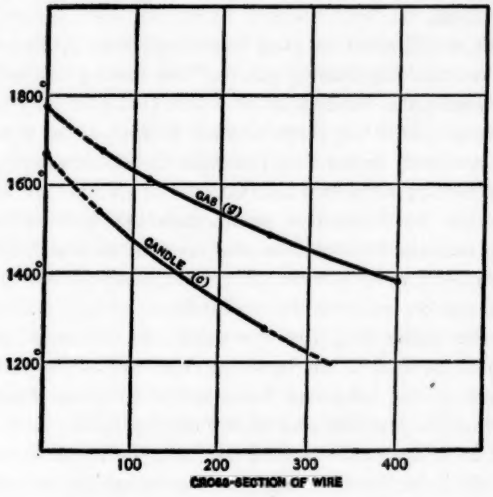

FIGURE 14.

upon a smooth curve (g) as shown in Figure 14. This curve, when extended to the line corresponding to zero cross-section, gave for the temperature of the flame 1780°, a temperature sufficient to account for the success of Smithells's experiment, already described, in which platinum wires of small diameter were melted in the outer sheath of such a flame. I found it easy, by holding a wire of the size used in junction IV. in a plane parallel to that of the flame, and moving it gradually toward the latter to verify his statement. The wire was readily melted.

It was not thought necessary to make further experiments upon this flame. The region selected was, so far as one could judge from the brightness of the luminous sheath, the hottest portion of flame. My measurements upon this region would lead to the conclusion that the *luminous sheath of ordinary gas flames is at least one hundred and twenty degrees lower than the corresponding region in the acetylene flame.* Luminous flames of ordinary illuminating gas would perhaps repay further study, but owing to the fact that such gas is an ever varying mixture and that it is burned under conditions of pressure, etc., such as to give a fluctuating character to the flame, the problem would have at

best an indefinite character from which studies of acetylene are free. In the latter case we have to deal with a definite fuel, and the velocity of the jets of gas from the burner is sufficient to give a high degree of stability to the flame.

The candle would seem an even less satisfactory subject of study in these respects than illuminating gas, but the fact of the melting down of Wollaston wire, the verification of which I have briefly described in an earlier paragraph of this paper, seemed to discredit so completely the low values commonly given that I decided to redetermine its temperature by the method already described.

The fact that the flame of a candle, mounted upon a fixed stand, would move steadily downward as the material of which it was composed burned away, made it convenient, without any serious modifications of my apparatus, to explore the temperature of the luminous sheath throughout the entire length of the flame. It was only necessary for this purpose to mount a candle upon the steel bar in the position previously occupied by the acetylene flame, and when it had reached such a length that the level of the rim of the cup lay below the level of the junction, to move the candle toward the latter by means of the micrometer screw until the junction began to be submerged in the luminous sheath of the flame. It was then easy by a series of slight adjustments of the flame to explore with the junction the entire surface of the luminous sheath from base to tip, measuring temperatures from time to time, and determining the position by means of the height of the junction above the rim of the candle cup. The latter observations were readily made by means of the image of the candle upon the ground glass of the camera. Explorations of the candle flame in the manner described were made with Junctions II. and IV., and the results obtained showed a degree of consistency much greater than the fluctuating character of the source under observation had led me to expect. Both sets of observations showed a maximum of temperature in the same region: that lying just above the tip of the interior dark zone of the flame. Readings were made by watching the movements of the candle flame and securing a balance of the potentiometer at times when the face of the junction was as nearly as possible in contact with, but not deeply submerged within, the luminous layer. Whenever the wire plunged to any considerable depth beyond the luminous surface, deposition of soot occurred with lowering temperature, and it was necessary to withdraw the junction into the non-luminous regions outside and to wait until the deposit had been burned off, before proceeding with the readings. In

computing the actual temperatures of the luminous sheath of the flame from these readings, I contented myself with the following rough approximation. The maximum temperatures shown by Junctions II. and IV. were plotted upon the same diagram used for the luminous gas flame. These temperatures were 1281° and 1546°; values which, as will be seen by inspection of Figure 14 (*c*), lie much below those of the corresponding readings for the luminous gas flame, but in such positions as to make it easily possible to draw through them a curve analogous in form to that obtained for the latter. Such a curve would cut the line of zero cross-section at about 1670°, which may, I believe, be taken as the approximate temperature of the hottest portions of the luminous sheath of the candle flame. Estimates of this temperature by the probably less accurate methods of drawing a straight line through the points in question and taking the point in which this line cut the line of zero cross-section to be the temperature of the flame, and estimates based upon the assumption that the true temperature is as many degrees above the temperature indicated by Junction IV. for the candle as it is for the gas flame, would lead to values respectively twenty-four degrees and forty degrees lower than that obtained by the method which I have adopted. I believe that the temperature just given (1670°) is much closer to the truth than that obtained under either of the other assumptions. Estimated temperatures for other portions of the luminous sheath were made by assuming that the correction to be applied to the readings obtained with Junction IV. would be the same in all positions. These values are given in Figure 14 which may serve in place of an ordinary table. The portions of the flame to which each reading refers are more readily indicated by giving such a diagram of the flame than in any other way.

The fact that, in the case of the acetylene flame and the ordinary gas flame, this method gives values high enough to account for the melting of platinum, but leads to an estimate of the temperature of the candle flame which is about one hundred degrees below the melting-point of that metal, would seem, at first sight, to throw the procedure into serious doubt. My experience with the method has, however, been such as to make an error of one hundred degrees in the estimation of the candle-flame temperature seem highly improbable. Messrs. Lummer and Pringsheim, in a recent communication to the German Physical Society,* give an estimate of the temperature of candle flames based upon a relation

* Lummer and Pringsheim, Verhandlungen der deutschen physikalischen Gesellschaft, 1899, p. 214.

which they have established between the position of the maximum in the energy curve of the spectrum of a source of light and its temperature. Assuming the radiating substance in the flame to have the properties of a black body, they find this temperature in the case of the candle flame to be 1687°, a value seventeen degrees above that which I have given.

To account for the fusion of Wollaston wire in the flame of a candle, one might consider the possibility of the existence in such a flame of layers of gas the temperature of which is much above the surrounding regions, and that these layers may be so thin that it would not be possible to submerge the thermo-junction completely in them. In such a case the junction would give a value approximate to the average of the temperatures of the gases with which it was brought into contact. Before assuming this structure of the flame, which really has nothing to support it save the necessity of accounting for the apparent discrepancy which I have just pointed out, it seemed wise to consider, on the other hand, whether the melting-point of the Wollaston wire was necessarily that of pure platinum. Such wires would naturally be made of ordinary commercial metal, the melting-point of which might vary considerably from that of the purer platinum used in the determination of melting-points. It is likewise readily conceivable that in the process of drawing within the silver coating, a certain amount of silver might be worked into the pores of the platinum and not be removed by the subsequent action of the nitric acid. The determination of the melting-point of even such minute wires is fortunately a simple matter by means of the form of thermo-element used in the calibration experiments already described. It is only necessary to wrap a piece of the wire to be tested around the junction, as shown in Figure 15, to cut it off so that the end of the loop extends slightly (about 0.05 cm.) beyond the face of the junction; and having mounted the junction in the usual manner, to move the acetylene up to it by means of a micrometer screw. I performed this experiment with a piece of the same Wollaston wire which I had succeeded in melting in the candle flame, and found its melting-point, as indicated by the electro-motive force of the junction, to be 1674°. To test the question whether this very low melting-point was due to the presence of silver undissolved by the nitric acid, a piece of the same wire was left in the acid for twelve hours, after which the

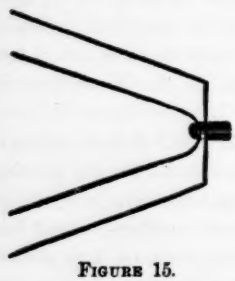

FIGURE 15.

melting-point was again tested in the manner just described. The result of this determination was 1687°. The latter reading was, I think, too high, since subsequent examination under the microscope showed that the loop of the wire behind the junction had been melted so that the junction was probably a few degrees too hot. It may safely be concluded from these determinations that the melting-point of the Wollaston wire was at least one hundred degrees lower than that of pure platinum.

Method of Checking the Constancy of the Acetylene Flame.

To secure as complete a check as possible upon the constancy of the flame, the following method, based upon the assumption that so long as the radiation from the flame remained constant, its light-giving power

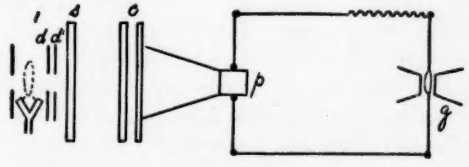

FIGURE 16.

would not vary, was employed. A diaphragm (*d*, Figure 16) similar to that interposed between the slit and the flame, and having an aperture of the same size, and mounted on the opposite side of the latter and a thermopile *p*, was placed at a distance of about 15 cm. from this opening. A second diaphragm, *d'*, with an intervening air space, served to cut off, in large part, the radiation from the heated metal. Two thin sheets of glass forming the sides of an empty cell *c*, of the kind used in the study of absorption spectra, etc., were placed between the cone of the thermopile and the second diaphragm; so that only those rays from the flame which were transmitted by the glass fell upon the face of the pile.

The thermopile was connected with a sensitive d'Arsonval galvanometer *g*, the circuit being kept permanently closed; and a double metallic shutter *s*, which could be raised or lowered so as to open or close the opening in the diaphragm next to the flame, was so mounted that it could be readily operated by an observer at the telescope of the galvanometer. When a reading of the radiation from the flame was to be made, the zero point of the galvanometer was noted, and this shutter was raised during the short interval of time necessary to bring the needle, which was not strongly damped, to its first turning point. The shutter was

then immediately closed in order to prevent further heating of the face of the thermopile. This throw of the galvanometer was taken as an indication of the intensity of the flame.

It was found that the thermopile would cool sufficiently within two minutes to admit of the repetition of the reading. These observations were taken by an assistant simultaneously with each setting of the spectrophotometer, the intention being to reject any spectrophotometric readings made at a time when the flame showed marked deviation from its standard intensity, and to reduce the readings to a uniform flame intensity under the assumption that for the small range of variation occurring from reading to reading, the change in the brightness of the flame would be proportional to the variations of this galvanometer reading from the mean of the whole set. In point of fact it was found that the flame rarely varied from the mean in the course of a set of observations by more than one per cent. From day to day, indeed, its intensity was usually within the limits stated above. Occasionally a larger variation was detected. None of these variations in the course of the present investigation reached values so great as to lead me to hesitate to apply the correction already referred to, and all the observations described in this paper have been reduced to a constant flame intensity by means of a correction factor obtained from the readings of the galvanometer.

Control and Measurement of the Temperature of the Carbon Rod.

The carbon rod, having been brought to the desired degree of incandescence by means of the current from a storage battery, was held at a constant temperature by varying the resistance placed in the battery circuit. The indications of the thermo-element inserted in the rod were noted by means of the potentiometer. The cells used in the measurement of the temperature of the carbon rod were the same as those employed in the calibration of the thermo-elements and in the study of the temperature of the acetylene flame.

The potentiometer having been balanced by looping the circuit containing the thermo-element around a sufficient portion of the resistance box to balance its current against that of the Clark cells, a condition which was indicated by the reduction of the galvanometer deflection to zero, the current was maintained at such a value as to hold the carbon at a constant temperature during the time necessary to complete measurements of the intensity of eight different portions of the spectrum, ranging from the extreme red to violet, with the corresponding portions of the spectrum of the flame. In order to insure the maintenance of this

constant temperature in the rod, an assistant made repeated observations with the potentiometer and readjusted the resistance in the battery circuit whenever necessary. Excepting at very high temperatures, where the rod was subject to rapid disintegration, it was rarely necessary to make any adjustment during the progress of a single set of observations. Readings of the current flowing through the carbon and of the fall of potential between its ends were made at the beginning and end of each experiment.

Spectrophotometric Observations.

It was my expectation, in planning this research, that whatever might prove true as to the character of the radiation from gray carbon, the distribution of energy in the spectrum from black carbon would change in such a manner with increasing incandescence as to become nearly or quite identical with that of the various luminous gas flames at temperatures corresponding to the temperature of the glowing carbon in those flames. I had also hoped, among other things, to be able to bring about a degree of incandescence approaching that of the acetylene flame itself, before the usefulness of the thermo-element as a means of measuring the temperature failed because of the melting of the platinum wire, and in this way to obtain a check upon my previous measurements of that flame; and at the same time to be able to determine the temperature of any given luminous flame in which the incandescent material consists of carbon particles by ascertaining the temperature of the carbon rod for which its surface had a spectrum corresponding in distribution of energy to that of the flame.

It will be seen from inspection of the curves to be discussed in a subsequent paragraph that this expectation was far from being realized, and that the distribution of energy in the spectrum of the carbon rod, instead of approaching that of the acetylene flame as the temperature of the rod increased, took on an entirely unexpected character. Even at low temperatures, that is to say up to about 1100°, the change in the spectrum was not of the comparatively simple character which had been anticipated, and shortly after passing the temperature of 1100°, unlooked for complications in the results arose. The energy in the yellow of the spectrum which from the beginning had been increasing at a relatively more rapid rate than either in the red or at the blue end, became so great as to give the distribution curve a form entirely contrary to expectation.

I was very slow to believe in the integrity of these results, and nearly

a year was spent in repetitions of the measurements before I could convince myself that the phenomenon was a genuine one. Measurements taken upon a great number of different rods and at different times showed the same result, however, and I was finally forced to the conclusion that the radiation from the carbon rods showed a much more complicated law of distribution than had been anticipated, and that a sort of selective radiation occurred such as to render the establishing of any simple relationship between the curve of distribution and temperature out of the question.

The hope of being able to make direct temperature measurements up to the melting-point of platinum was also disappointed. While the carbon rods at comparatively low temperatures showed a fair degree of stability under the action of the current, they appeared to undergo a decided change of behavior at about 1400°, and before that temperature a rather rapid disintegration, showing itself by a change of resistance, manifested itself. This effect appeared to be similar to that which shortens the life of the filaments of incandescent lamps when these are subjected to a large amount of current. It appears, moreover, that at these high temperatures the carbon tends to combine with the metals of the thermo-element, affecting the electromotive force very much as the vapors in a furnace have been found to do. The thermo-elements inserted in the rod begin, in consequence of this action, to fail of their purpose. It was found that after exposure to temperatures much above 1400°, the electromotive force corresponding to even lower temperatures was considerably below the normal. I was consequently compelled to abandon the attempt to measure directly temperatures above this point, although it was possible to bring the rods to a higher degree of incandescence for a length of time sufficient to perform the spectrophotometric observations. In order to obtain at least an approximate estimate of these temperatures, I made use of the fall of potential between the terminals of the rod, and also of the current of the heating circuit; and by extending these curves, which, throughout the range of measured temperatures were found to be nearly straight, to the high temperatures which I wished to estimate, to obtain some idea, even if not an exact one, of the latter.

In expressing the results of the photometric measurements already described, I have made use of two forms of curve. One set of curves, in accordance with the nomenclature proposed in my original paper on the visible radiation from platinum, and later adopted by Paschen and other writers, I may call *isotherms*. These curves give in terms of the

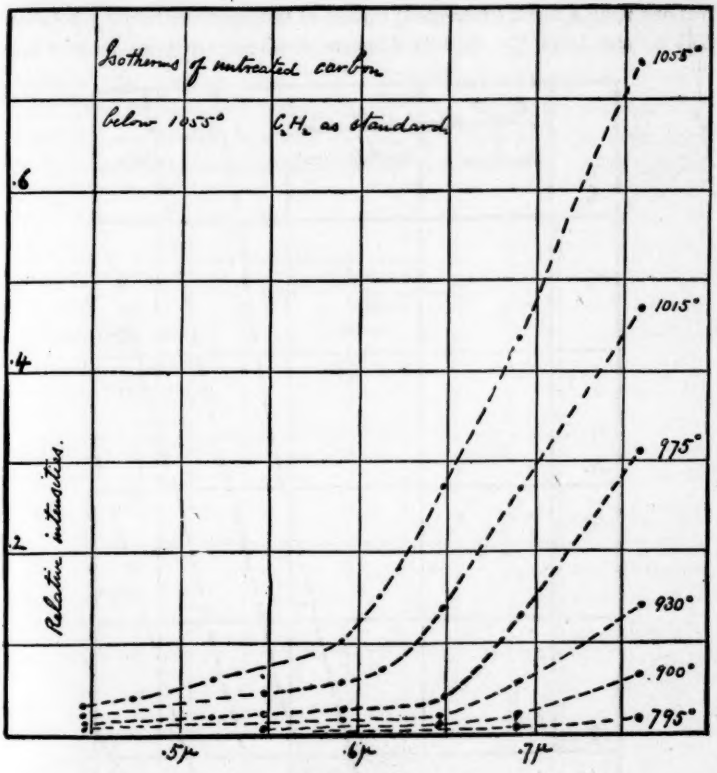

FIGURE 17.

corresponding wave lengths of the comparison source (in this case the acetylene flame), the relative distribution of energy in the visible spectrum from the carbon rods. The other curves, which I have termed *isochroms*, indicate the rise in the energy of any particular wave length of the visible spectrum, with increase of temperature. Each of these curves, taken by itself, is entirely independent of the nature of the light of the comparison source, but the absolute relation of such curves to one another can only be obtained when we know the distribution of energy in the spectrum of that source. By means of the isochroms, it is, however, possible even without this knowledge to compare the rise in intensity of any single wave length of the spectrum with increasing temperature.

The set of curves shown in Figure 17 are plotted directly from obser-

vations upon a black (untreated) carbon at temperatures ranging between 795° C and 1055° C. In this diagram abscissae are wave lengths and

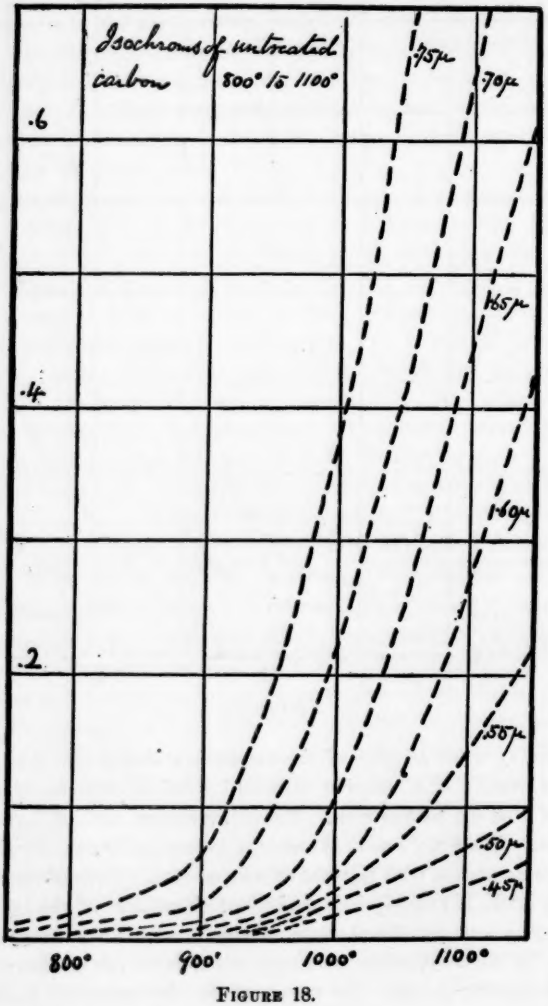

FIGURE 18.

ordinates are ratios of the brightness of the spectrum of the carbon rod in each region to that of the corresponding region in the spectrum of

the acetylene flame. A noteworthy fact exhibited by means of these curves is the relatively rapid increase of intensity in the middle of the spectrum. In passing from 930° to 1055° the brightness of wave length .76 μ, increases 5.3 times; that of .70 μ, 7.2 times; that of .60 μ, 13.5 times, *and that of* .50 μ *only* 9 *times.* We have here the beginnings of a process which becomes more marked in its effects as higher temper-

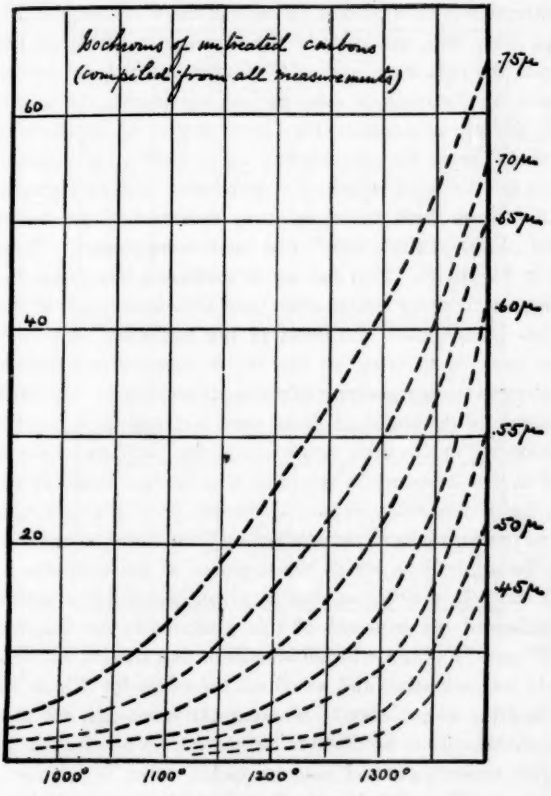

FIGURE 19.

atures are attained. From 1100° upwards it was found much more difficult to obtain satisfactory readings. The carbon rods which I had brought from Paris for this investigation would not stand prolonged heating and it was necessary to replace them frequently.

In order to bring the observations upon the various rods to a common scale, isochroms from the readings for each rod were plotted. The general character of these curves is shown in Figure 18, in which the isochroms corresponding to the isotherms of Figure 17 are given. From the ordinate at 1000° of the isochrom for .6μ, which for convenience was taken as unity for the entire set, a reduction factor was obtained by means of which all the curves for all the carbons were brought to the same scale. A new set of isochroms was then plotted for each of the wave lengths .75μ, .70μ, .65μ, .60μ, .55μ, .50μ, and .45μ, in the drawing of which all the observations upon the rods were used. While this method did not bring the various sets of observations into perfect agreement, the results were sufficiently definite to indicate with a close degree of approximation the trend of these curves for temperatures up to 1400°. The result of this compilation for the wave lengths just mentioned is shown graphically in Figure 19. From these curves in turn, isotherms for the temperatures 900°, 1000°, 1100°, 1200°, 1300°, and 1400° were plotted. These curves are given in Figure 20. Had the law of increasing intensities throughout the spectrum with rising temperature been that anticipated at the beginning of this investigation, the trend of the isochroms would necessarily have been such as to bring all the curves together at a common point corresponding to the temperature of the acetylene flame. In other words, if the spectrum of the acetylene flame were identical throughout with that of the carbon rod at the same temperature, the isotherm of the spectrum of the rod at that temperature would be a horizontal line. It is obvious, however, that if the wave lengths of the middle of the spectrum should continue to increase faster than the red and the violet, a condition would presently be attained in which the ordinate of the isotherm would be greater in the yellow or green than at either end of the spectrum. We see indications of the approach of this condition in the diagram of isochroms (Figure 19), from which it is evident that the curves for .65μ and .60μ would cut each other and would cut the curve for .70μ at some temperature not far above 1400°; whereas the isochroms for the shorter wave lengths would not be likely to cut the curves for the red until some much higher temperature had been reached.

The curves in Figure 20 show the nature of this unexpected development of the spectrum in a somewhat different aspect. It will be seen from this figure that the growth in the extreme red so far lags behind that of the full red, and this in turn behind that of the orange, and this in turn behind that of the wave length .6μ, that at 1400° the isotherm, instead of being convex to the base line throughout, actually becomes convex. I

have indicated by means of lighter lines the form of curve which might have been expected had the type of isotherm which exists at lower temperatures been maintained.

Above 1400° it was found impossible to obtain consistent readings on account of the rapid disintegration of the carbon rods; but I was able to satisfy myself after repeated trials that at temperatures not far above 1500° this change in the character of the isotherms had progressed to the

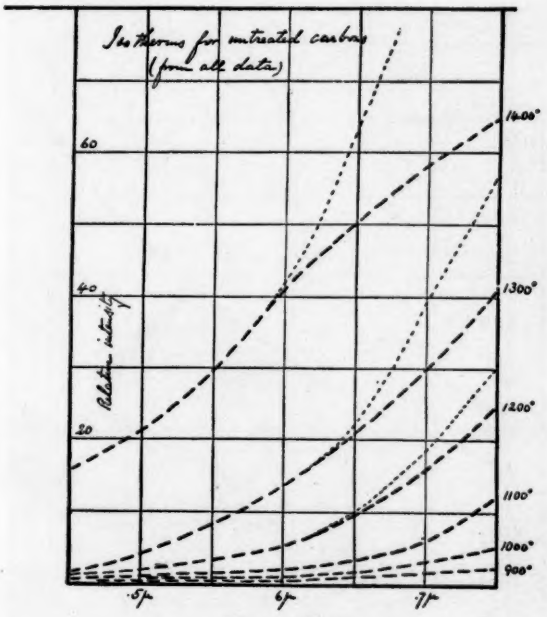

FIGURE 20.

point at which the yellow regions of the spectrum possess an ordinate greater than that of the extreme red or of the blue or violet. At a temperature about 300° below that of the acetylene flame, then, the spectrum of the carbon rod was relatively weaker in the red, stronger in the yellow, and weaker again in the shorter wave lengths than the spectrum of the flame. There is no reason to suppose that had it been possible to heat the rods to the temperature of the flame itself the law of increase of intensity for the various wave lengths would have undergone such radical modifications to bring the two spectra at that temperature into identity.

Spectrophotometric Measurements upon Rods with Treated Surfaces.

In order to compare the radiation of rods of black surface with those the surfaces of which have acquired a gray coating by treatment in hydrocarbon vapor, rods were mounted in the usual manner, and after the exhaustion of the air from the metal box, gasoline vapor was allowed to enter until the atmosphere surrounding the rod was saturated. The

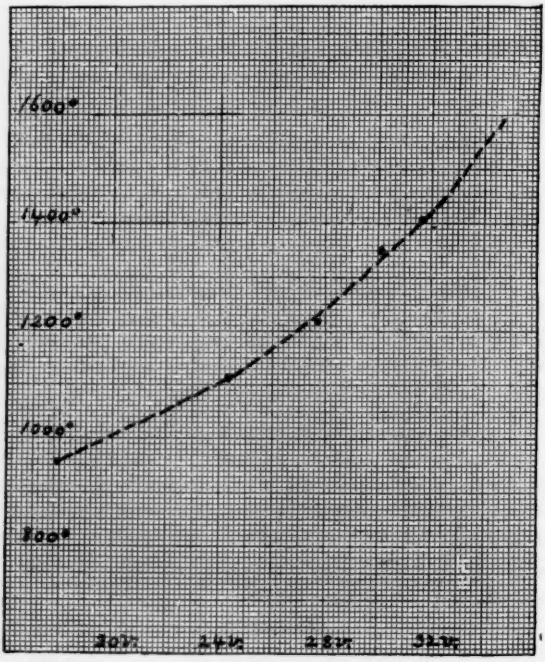

FIGURE 21.

rod was then brought several times to a high state of incandescence for a few seconds at a time, by which means the entire surface became coated with a gray deposit of carbon similar to that obtained by the treatment of incandescent lamp filaments. The metal box was then again pumped out and spectrophotometric measurements similar to those already described were made upon the radiation from the treated surface. It was thought that as the result of this treatment the carbon rods would stand

a more prolonged exposure at high temperatures, and that thus it might be possible to extend the measurements beyond the point reached with the rods of black surface. This was found to be the case.

As has already been indicated in a previous paragraph, the indications of a thermo-junction at these high temperatures was subject to serious suspicion. I was obliged to content myself, therefore, with estimations of

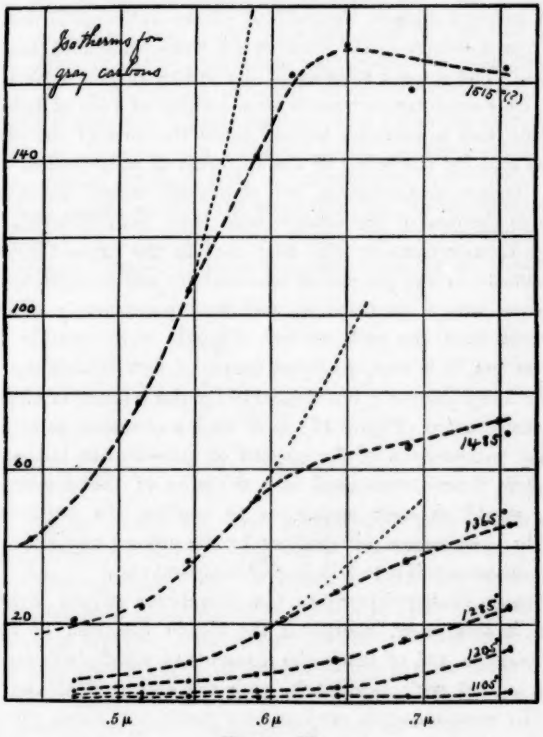

FIGURE 22.

the temperature based upon the difference of potential between the terminals of the rod. Fortunately the relation between the electromotive force and the temperature up to 1400° was of such a character that but little error was to be feared in extrapolating. The relation between electromotive force in volts and temperature is shown in Figure 21. From this curve temperatures above 1400° were determined.

The work upon treated carbons was confined chiefly to high temperatures, a sufficient number of readings within the range already explored with the untreated carbons being taken to show that the distribution of intensities at the lower temperatures did not differ materially from that in the spectrum of the former. The set of isotherms given in Figure 22 will suffice to indicate the general character of the results. It will be seen that in this case, as in that of the untreated carbon, the concavity of the curve between .6μ and the red end of the spectrum is well marked at 1365°; and that at 1515° there was a well-pronounced maximum at about .65μ. The greater stability of the treated carbon made it possible to obtain consistent measurements on a number of rods at temperatures above 1500° and to establish beyond doubt the form of the curves. It is obvious that for the study of the spectrum of incandescent carbon at this and higher temperatures the conditions would be much more favorable in the case of the incandescent lamp than with rods mounted in a large vacuum chamber like that used in the present investigation. Lamp filaments in the process of manufacture are brought by thorough carbonization into a condition to withstand permanently much higher temperatures than the rods at my disposal were capable of doing. There is as yet, it is true, no direct means of determining the temperature of the lamp filament; but the curve for the relation of electromotive force to temperature (Figure 11) is of such a character as to lead us to expect that comparisons of the spectra of incandescent lamps, in which electromotive forces were used as a criterion of the degree of incandescence, would at least enable us to confirm the existence of the remarkable phenomenon brought out by the present experiments and to extend observations of it to still higher temperatures.

Mr. Ernest Blaker has, since the completion of the measurements described in this paper, compared the visible spectrum of lamps with treated filaments, and of lamps the filaments of which before exhaustion had been coated with lampblack, with the spectrum of the acetylene flame. His measurements confirm very completely those which I have described in this paper, and contribute important evidence in favor of the existence of this anomaly in the law of distribution of intensities in the spectrum of glowing carbon.

Theoretical Aspects of the Foregoing Data.

The efforts of students of radiation have of late years been directed particularly to the testing of the various formulae by means of which the mathematical physicists have attempted to express the intensity of

radiation as a function of wave length and temperature. The equation reached from quite different points of view by Wien * and by Planck,†

$$I = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}},$$

in particular, has been the subject of exhaustive discussion and of experimental tests. To this end Paschen ‡ determined with the bolometer the distribution of energy in the infra-red spectra of various bodies from 15° C to 1300°. The materials thus subjected to measurement were oxide of copper, platinum, lampblack, and graphitic carbon. The range of wave lengths explored extended from 9.2μ to 0.7μ. Lummer and Pringsheim § made similar determinations upon the ideal black body, and Lummer and Jahnke ‖ finally repeated these measurements in the case of the black body and of platinum. Wanner,¶ working with Paschen, made careful spectrophotometric measurements of the visible radiation from the ideal black body. To test the applicability of the Wien-Planck formula to these measurements, the equation is given the form, —

$$\log I = \gamma_1 - \gamma_2 \frac{1}{T};$$

in which

$$\gamma_1 = \log (c_1 \lambda^{-5}),$$

$$\gamma_2 = \frac{c_2}{\lambda} \log e.$$

The isochromatic curves are then plotted with the logarithm of the intensities as ordinates and the reciprocal of the absolute temperature as abscissae. The agreement of the equation with the observations is found in the fact that isochroms thus plotted, at least as far as the work of Paschen and Wanner is concerned, always take the form of straight lines, and that the quantity c_2 computed for various wave lengths is found to be a constant. Lummer and Pringsheim, on the contrary, find in the discussion of their measurements that the constant, c_2 increases steadily with the wave length from 13,500 at $1.2\ \mu$ to 16,500 at $5\ \mu$, and 18,500 at $0.3\ \mu$. The value of c_2 computed by measurements from

* Wien, Wiedemann's Annalen, LVIII. 662 (1896).

† Planck, Drude's Annalen, I. 69 (1900).

‡ Paschen, Wiedemann's Annalen, LVIII. 455 (1896); also LX. 662 (1897).

§ Lummer and Pringsheim, Deutsche phys. Gesellschaft, I. 23, II. 163 (1900).

‖ Lummer and Jahnke, Drude's Annalen, III. 283 (1900).

¶ Wanner, Drude's Annalen, II. 141 (1900).

Beckman at wave length 24 was found to be 24,250. Lummer and Pringsheim find, moreover, that the logarithmic isochroms, especially when extended to higher temperatures, are not straight lines, but show a slight convexity towards the $\frac{1}{T}$ axis.

Exception has also been taken to the Wien-Planck formula on the ground that it gives for infinite temperatures a finite limit to the value of the intensity, a result which Rayleigh * in a recent paper has characterized as *physically improbable.*

Rayleigh proposes the form

$$I = c_1 T \lambda^{-4} e^{-\frac{c_2}{\lambda T}}$$

but Lummer and Pringsheim find that this likewise fails to properly express their experimental results. Lummer and Jahnke propose, in view of these discrepancies, to give the equation the general form

$$I = C T^5 (\lambda T)^{-\mu} e^{-\frac{c}{(\lambda T)^\nu}},$$

an expression which coincides with Wien's formula for $\mu = 5$ and with Rayleigh's for $\mu = 4$. They find the measurements of Lummer and Pringsheim satisfied when μ lies between 4.5 and 5, and ν lies between .9 and 1.0. If we accept the value $\mu = 5$ and $\nu = 0.9$, this equation always leads to a finite value of intensity for infinite temperature. All other values of these quantities give infinity as the limit of intensity.

Whether logarithmic isochroms or the value of the quantity c_2, computed from measurements upon carbon rods, would aid in deciding between the various equations under discussion is a question. The data given in this paper would not lead us to class the carbon rods studied as *black bodies.* The emissive power of various forms of carbon is well-known to be smaller than that of the ideal black body, and there is no reason to suppose that it is independent of the temperature. The relative lagging behind of the intensities in the red might perhaps be taken as an indication of a tendency to approach the infinite maximum demanded by the Wien-Planck formula; but the isochrom for .76 shows that the effect, if it exists, must be looked for at some much higher temperature than that covered by these measurements. In spite of these doubts as to the applicability of the measurements on carbon rods to the problem of the

* Philosophical Mag., XLIX. 539 (1900).

law of radiation of the ideal black body, I have plotted the various isochroms obtained in the course of this investigation in logarithmic form; absolute temperatures being taken as abscissae and the logarithm of the intensity as ordinates. These logarithmic isochroms, as will be seen from

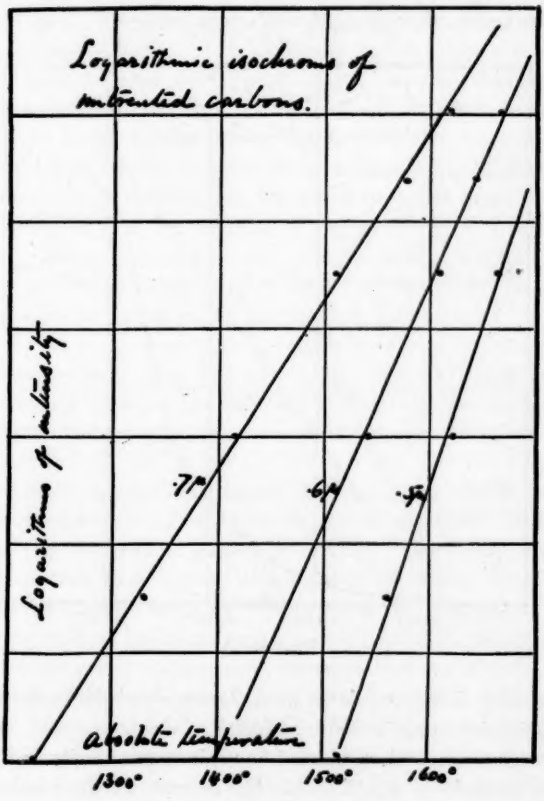

FIGURE 23.

Figure 23, in which three curves from Figure 19 are reproduced, are straight lines. The range of temperatures is doubtless much too small to bring out the curvature found by Lummer and Pringsheim, but the curves show clearly the change of direction with the wave length men-

tioned by those writers on page 222 of their paper before the German Physical Society.*

For very high temperatures no experimental data for the radiation from carbon exist excepting the measurements described by Lucas. † It has been rather the fashion to leave Lucas's work altogether out of account as being hopelessly at variance with more recent results. Kayser, ‡ for example, after giving Lucas's data, says, —

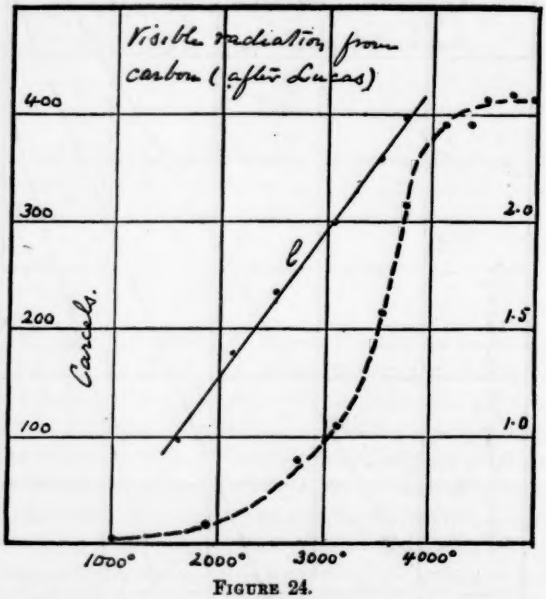

FIGURE 24.

Zu falschen Schlüssen gelangt auch Lucas, durch Versuche welche das Verdampfen der Kohle in Frage zu stellen scheinen.

His results, nevertheless, which I have given graphically in Figure 24, appear to me to be of significance. His formula for the relation of temperature to current, $t = 25\ i$, must of course be regarded as only approximately correct even at moderate temperatures. The curve for the relation between the current in a carbon and the temperature, up to about

* Lummer and Pringsheim, Verhandl. d. Deutschen Physikal. Gesellsch. (1899) p. 222.

† Lucas, Comptes Rendus, C. 1454 (1884).

‡ Kayser, Handbuch der Spectroscopie, I. 157.

1500°, does however not vary widely from a straight line. Beyond these temperatures it is a matter of extrapolation, but the same thing is true of all other attempts to estimate very high temperatures. The curve *l*, for the relation of the logarithm of the intensities and the temperatures, which I have also given in Figure 24 (between 1500° and 3750°), is in the case of Lucas's measurements nearly straight; so that in so far as this is a criterion, his curve up to this point may be said to conform to the Wien-Planck equation. It is significant that Lucas's curve shows an inflection point between 3500° and 4000°, becoming concave to the axis of temperatures. This is the temperature at which, according to nearly all the newer determinations, carbon, as in the crater of the arc, approaches its maximum condition of incandescence. At about 3750° the electrical energy developed in the rod is doubtless largely expended in the disintegration or vaporization of the carbon, so that a maximum degree of incandescence is approached. At the point at which this process begins current can no longer be taken as a measure of the temperature. The very slight falling off in the photometric measurement of intensity does not appear to me to warrant the conclusion drawn by the author that a maximum has been passed at the current value to which he assigns the temperature 4750°. The difficulty of obtaining consistent readings under conditions existing in such work would amply account for so slight a discrepancy.

Lucas's work appears, in a word, to warrant the following rather important conclusions. First, that up to about 3750° current and temperature in the case of carbon rods heated electrically are nearly proportional. We have in favor of this point two checks, — the straightness of the logarithmic curve and the fact that the inflection of Lucas's curve corresponds, as has already been pointed out, to the recognized temperature of the crater of the arc. Secondly, that for a wide range of temperatures photometric intensity, like the intensity of total radiation, follows the logarithmic law of increase. Third, that after the temperature of the crater has been attained a considerable additional increase in incandescence results from the application of further current before the maximum is finally attained. This agrees with the observations of Moissan,* that many reductions in the electric furnace which do not occur with moderate currents become possible by increase of the current strength. If, as seems proper, we ascribe the rapid approach of Lucas's curve to a finite maximum to the utilization of the energy of the cur-

* Moissan, Comptes Rendus, CIX. 776 (1894).